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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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13. ABSTRACT

This report summarizes results during the period 1 July 1971 through 31 December 1971. The applied research is now being conducted by E. F. Industries, Inc. under subcontract to Martin Marietta corporation. Close liaison is being Maintained between E. F. Industries, Inc. and the University of Denver to further inhance the coupling of science and technology, one of the major goals of the Center for High Energy Forming. Section I of this report describes ~~those~~ areas of applied research where definite programs pointed toward hardware applications have already been established. These include thick walled tube expansion, die stresses, and applications of explosive welding to hardware configurations. The work on explosive expansion of thick walled tubes is directed toward reduction of process cost and an accurate deremination of the process economics. Explosive compaction of metal powders is directed toward production of forging preforms for turbine discs, turbine buckets, etc. The explosive welding work will concentrate on the production of components applicable to helicopter spars, rotors, hubs, and dual hardness armor.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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Energy Transfer						
Strain Rate Effects						
Explosive Welding						
Mechanical Properties Before & After Forming						
Exposive Thermomechanical Processing						
Explosive Powder Compaction						

(Continuation of ABSTRACT)

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Other research is reported on perforated dies, explosive forming of thick walled domes, use of high explosive pressure for increased ductility, analysis and design of facilities for explosive welding and explosive welding of steel boiler components.

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The basic parameters for powder metal compaction have been established for some powders and for compaction of steel-tungsten composites. Preliminary results of explosive thermomechanical processing of 17-7PH stainless steel and a Beta III titanium alloy. Prediction and control of explosive pressure history in thick wall tubes is being investigated via strain gage measurements. Also, the energy transfer from a centrally located charge to a flat blank is being investigated. The explosive welding research is directed toward diffusion and defect studies, as well as welding parameters and thickness limitations.

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I. E. F. INDUSTRIES, INC.

1. Thick Walled Tube Expansion

Principal Investigators: J. D. Mote, L. K. W. Ching

One of the major costs in producing compressive residual stresses in thick walled tubes using explosive bulging methods is the cost of the stainless steel radial piston. The selection of stainless steel as the radial piston material during the subscale development program was arbitrary, based only on availability and schedule. However, the use of a different piston material must produce the correct pressure-time pulse to properly autofrettage the thick walled tube. A mathematical analysis is now being conducted by the University of Denver to determine the tube thickness and explosive loading required for autofrettage using a mild steel tube. Upon completion of the analysis, E. F. Industries, Inc. will autofrettage two subscale tubes based on the parameters developed by the analysis. Subsequent to verification of the successful autofrettage, a process economic evaluation will be conducted.

2. Explosive Compaction of Metal Powders

Principal Investigators: J. D. Mote, L. K. W. Ching

The most promising area for immediate use of explosive powder compaction methods is for forging preforms for compressor discs and preforms for turbine discs and turbine buckets. E. F. Industries, Inc., in close liaison with University of Denver personnel, plans to quickly attack the problems of producing such explosively compacted powder metallurgy parts. The potential advantage of this process is to provide greater homogeniety in the material, thus eliminating the lamination problems encountered with other processes.

Our initial studies will involve compaction of powders in sealed metal containers. This study will progress along two fronts, namely, container design and explosive loading required to produce a given density. Several container wall thicknesses will be used to determine the container configuration required to prevent canister fracture. Three different geometries will be used in this phase. The geometries will be a pancake, a cylinder and a hollow tube. Once the container designs are established, additional shots will be performed to obtain the highest density for each configuration and wall thickness. These tests will then provide a baseline for the density studies and should be completed in 3 1/2 months.

The density studies will be based on the earlier studies. The container will be selected and several different metal powders will be compacted based on the previous results. Metal powders will be selected from the following classes:

a. ferrous alloys

b. stainless steel alloys

c. superalloys

d. refractory alloys

These alloy classes represent the most interesting and challenging classes and should represent a wide range of material properties. Loadings will be varied in this testing phase to obtain maximum densities for each type of powder. Once this study is completed, the problem of compacting powders in a hardware configuration can be studied.

Hardware configurations will, naturally, vary according to the specific requirement; however, there are several configurations which appear more often than others. One or two of these representative configurations will be selected for further study. Container and load versus density studies similar to the earlier studies will be conducted to determine if the high densities achieved with simple shapes can be achieved in more complex shapes.

The program outlined above should provide an insight to the problems of compacting metal powders in a container, compacting various types of metal powders, and compacting complex shapes. The results derived will provide data for several areas of practical applications.

3. Die Stresses

Principal Investigator: L. K. W. Ching

Analysis of the experimental results in the die stress program is being conducted and a final report is being prepared for inclusion in the annual report.

4. Applications of Explosive Welding to Hardware Configurations

Principal Investigators: J. D. Mote, L. E. Jensen

A preliminary program plan for exploitation of explosive welding technology applied to specific hardware configurations of interest to D.O.D. Departments has been prepared. This program will emphasize production of joints for such applications as helicopter spars, rotors, hubs, weld retainers, etc. Another area of extreme interest is explosively bonded and explosively formed composite armor including dual hardness armor. A concentrated six month experimental program is being developed to demonstrate the feasibility of the process in these areas.

II. UNIVERSITY OF DENVER

1. Explosive Powder Compaction

Principal Investigator: H. Otto

Graduate Students: D. Witkowsky and T. McClelland

This area of research is divided into two studies: (a) the fabrication of rolling preforms and (b) the compaction of composites. In both studies, steel powder has been used for the basic material with tungsten filaments being used in the composite study.

a. Compaction of Preforms

Compacts of Ancorsteel 1000 Iron Powder had been made earlier in the program using explosive loading ratios of 1.1:1.0, 0.8:1.0, and 0.6:1.0 (weight dynamite to weight steel powder). Very little difference in hardness was noted from compact to compact, as an inspection of Table II.1.1 indicates. Even a comparison with a conventionally pressed compact did not indicate a large difference in hardness, even though the conventionally pressed compact was less dense.

Sintering experiments were conducted in a gettered hydrogen-argon atmosphere. Both time and temperature were used as variables in these experiments. Results of these tests are presented in Tables II.1.2 and II.1.3.

As an inspection of these tables indicates, the specimens actually decrease slightly in density as a result of sintering. This decrease varies over a wide range and is more pronounced in the conventionally compacted specimens. Although there were no significant changes in specimen dimensions as a result of sintering, changes in weight were observed. The decrease in density noted is a result of weight loss with no corresponding decrease in volume.

Metallographic examinations are underway at the present time to determine the type of changes that occur during sintering. These studies should be completed in the near future.

b. Compaction of Steel-Tungsten Composites

A double-acting piston arrangement is being used with Red Cross 40% Extra dynamite as the explosive charge.

Problems have been encountered in obtaining a uniform wire distribution and cracking in the composite. A wire-winding apparatus has been built which now allows a uniform wire distribution to be obtained. Wire braces with 5-mil tungsten wire 5 mils apart

Table II.1.1 Hardness Readings on Green Compacts with 1/4-inch Ball and 15 Kg Load

Type of Explosive	Loading Ratio	Thickness Compact, in	Average Hardness
40% RCE	1.1:1.0	1/2	87
40% RCE	0.8:1.0	1/2	88
60% GD	1.1:1.0	1/2	87
SWP-5	1.1:1.0	1/4	85
SWP-5	0.8:1.0	1/4	86
SWP-5	0.6:1.0	1/4	85
No Explosive	31.2 tsi	1/4	84

Table II.1.2 Results of Sintering Tests on Explosively and Conventionally Compacted Steel Specimens After Sintering for One Hour at Various Temperatures

Sample Identification	Sintering Temp., °F	Density, % of Theoretical		Change in Density, %
		Before	After	
EC 1.1:1.0	800	96.3	93.4	-2.9
	1000	96.9	94.6	+2.2
	1200	95.4	94.3	-1.1
	1400	96.6	94.7	-1.9
	1600	96.2	95.7	-0.5
	1800	95.0	94.4	-0.6
	2050	94.9	97.5	+2.6
	2200	97.5	96.9	-0.6
	2400	97.1	96.4	-0.7
EC 0.6:1.0	800	97.0	95.7	-1.3
	1000	95.5	94.9	-0.6
	1200	97.3	95.8	-1.5
	1400	96.3	94.5	-1.8
	1600	97.2	95.9	-1.3
	1800	96.6	06.1	-0.5
	2050	95.1	96.6	+1.5
	2200	96.3	95.9	-0.4
	2400	96.6	95.5	-1.1
CC 31.2 tsi	800	83.2	82.0	-1.2
	1000	83.4	82.5	-0.9
	1200	82.4	81.1	-1.3
	1400	82.8	80.4	-2.4
	1600	84.5	81.8	-2.7
	1800	85.2	83.7	-1.5
	2050	85.5	83.1	-2.4
	2200	83.3	80.4	-2.9
	2400	84.1	80.6	-3.5

Table II.1.3 Results of Sintering Tests at 2050°F for Various Times

Sample Identification	Sintering Time, hr.	Density, % of Theoretical Before	Density, % of Theoretical After	Changes in Density, %
EC 0.8:1.0	1/4	96.3	95.5	-0.8
	1/2	95.8	94.8	-1.0
	3/4	96.7	96.1	-0.6
	1	94.7	96.1	+1.4
	1-1/2	96.4	96.1	-0.3
	2	96.5	96.0	-0.5
	3	96.7	96.4	-0.3
	6	95.4	96.3	+0.9
CC 32.1 tsi	1/4	85.0	84.9	-0.1
	1/2	86.0	85.8	-0.2
	3/4	86.4	85.9	-0.5
	1	85.5	83.1	-2.4
	1-1/2	84.7	84.5	-0.2
	2	84.3	84.3	0
	3	84.9	83.4	-1.5
	6	83.6	82.4	-1.2

have been made and used. The steel powder is now being vibrated around the wire harps for varying time periods using a modified Syntron Vibropolisher. This is to insure that the powder fills all the voids around the wires and helps eliminate weakness planes.

A number of die modifications have been tried in an attempt to eliminate the cracking problem. Different types of spacers between the wire braces and the die and varying sizes of piston top-plates have been tried with little success. Currently a new die is being built with larger overall dimensions. It is believed that the more massive die will reduce the elastic spring-back which seems to be the major cause of cracking.

Portions of the final composite away from cracked regions are well compacted and, after sintering, show good matrix-fiber bonding with no brittle interface region. Once the cracking problem is overcome, mechanical testing will be done to determine the properties of the composites.

2. Explosive Thermomechanical Processing

Principal Investigator: R. N. Orava

Graduate Student: J. P. Allen

The investigation of dynamic thermomechanical processing (TMP) is continuing. The effects are being studied of the incorporation of cold rolling or explosive forming, as the mechanical working stage, into the heat treatment schedules for semi-austenitic precipitation-hardenable stainless steel (17-7PH) and an age-hardenable beta-titanium alloy (Beta III). Recent results are presented below.

The standard thermal processing procedure for 17-7PH steel is given in Table II.2.1 and involves:

1. solution heat treatment;
2. austenite conditioning to precipitate $M_{23}C_6$ and render the austenite less stable;
3. transformation to martensite, by cooling or cold working;
4. precipitation hardening, which serves as both a martensite temper and an aging treatment.

Forming was inserted between each of Steps 1 and 2, 2 and 3, and 3 and 4 above. The martensitic transformation in Step 3 was effected thermally prior to forming.

Room-temperature tensile properties were compared after thermal processing, conventional TMP by cold rolling, and dynamic TMP by explosive stretch-forming of rectangular workpieces. The data are presented in Table II.2.2.

When the mill-annealed stock was deformed and then aged at $100^{o}F$ for 1 hr., the terminal strengths increased in the predicted manner with increasing forming strain. Also, for an equivalent reduction in thickness, the yield and ultimate strengths after explosive forming and aging are lower than those after rolling and aging. For example, for a forming strain of about 13%, the yield strength associated with explosive TMP is about 16% lower than after conventional TMP, and the ultimate strength, 6% lower. Although these differences are not particularly great, one should be aware of this factor for design purposes. It is best understood in terms of a reduced propensity for strain-induced martensitic transformations as the rate of deformation increases. This tendency is experimentally well established. A less likely explanation would be the acceleration of aging due to the nature of the defect structure generated at explosive forming rates. Studies are presently underway in an attempt to isolate these possibilities.

Table II.2.1 Standard Heat Treatments for ARMCO 17-7 PH

Solution Heat Treated
(Mill Annealed 1950 ± 25F)
RESULT: Condition A

Fabricate

t 1400 ± 25 F
d 90 Minutes

Austenite Conditioning

Heat to 1750 ± 15 F
Hold 10 Min. Air Cool
RESULT: Condition A-1750

Cool within 1 hr.
60 + 0 – 10 F
d 30 Minutes Min.
JLT: Condition T

Trans-formation

Cool within 1 hr.
to – 100 ± 10 F
Hold 8 hrs.
RESULT: Condition R-100

t to 1050 ± 10 F
d to 90 Min. Air Cool
JLT: Condition TH 1050

Precipi-tation Hardening

Heat to 950 ± 10 F
Hold 1 hr. Air Cool
RESULT: Condition RH 950

Precipitation Hardening

Cold Rolled at Mill
RESULT: Condition C

Fabricate

Heat to 900 ± 10 F
Hold 1 hr., Air Cool
RESULT: Condition CH 900

Table II.2.2 Room-Temperature Tensile Properties of 17-7PH Stainless Steel Following Thermal Processing, Conventional TMP, or Explosive TMP.

Forming History*	Forming Strain (in/in)	0.2% YS (ksi)	UTS (ksi)	Total Elong. (%)	R.A. (%)
(a) Condition A + Cold Work → Condition CH900					
UD	0	52.0	137.1	38.8	52.7
CR	0.084	90.1	148.8	32.0	47.3
	0.112	106.3	159.6	30.0	49.1
	0.129	114.9	160.4	29.8	45.2
EF	0.129	96.2	150.6	31.1	42.8
Nominal	0.30	115	178	10	
	0.60	190	220	5	
(b) Condition A + Cold Work → Condition TH1050					
UD	0	181.8	194.9	6.5	27.0
CR	0.084	179.1	191.4	10.0	33.8
	0.112	185.9	194.7	6.1	33.0
EF	0.084	191.4	201.9	5.9	28.9
	0.112	187.4	199.1	8.1	36.4
Nominal	0	174.5	187.5	10.5	
	0.30	165.5	183.8	11.8	
(c) Condition T + Cold Work → TH1050					
UD	0	181.8	194.9	6.5	27.0
CR	0.024	192.6	197.9	3.8	19.0
EF	0.024	192.3	199.8	5.5	32.5
Nominal	0	174.5	187.5	10.5	

* UD: undeformed; CR: cold rolled; EF: explosively formed

Table II.2.2 (Con't.)

Forming History*	Forming Strain (in/in)	0.2% YS (ksi)	UTS (ksi)	Total Elong. (%)	R.A. (%)
	(d) Condition A1750 + Cold Work → RH950				
UD	0	211.4	222.3	6.9	31.4
CR	0.022	201.4	216.3	8.3	12.6
EF	0.022	140.1	193.5	11.4	34.6
Nominal	0	220	235	6	
	(e) Condition R-100 + Cold Work → RH950				
UD	0	218.1	229.0	8.4	36.5
CR	0.025	183.3	216.1	11.5	35.5
EF	0.025	215.9	228.9	10.7	34.2
Nominal	0	220	235	6	

* UD: undeformed; CR: cold rolled; EF: explosively formed

Generally, imparting a large amount of strain in Condition A prior to converting to TH1050 requires a modification of the austenite conditioning temperature from 1400 to 1550°F, and the transformation cooling conditions to 0°F for 4 hrs. This will restore to undeformed TH1050 levels the properties shown in Table 2(b) for 30% strain. Significantly, it would appear that this modification is unnecessary for the lower forming strains (8.4 and 11.2%) examined herein, particularly when material in Condition A is explosively formed. The strengths are increased relative to thermally processed control material by an average of 8% for yield and 3% for ultimate strength in this strain range. Moreover, the ductility is raised slightly rather than falling off as might be expected.

When 17-7PH steel is formed in the transformed condition (T) prior to aging to TH1050, both rolling and explosive forming introduce a small increase in the final strength levels. Whereas the former leads to substantial reductions in ductility, explosive forming leaves the ductility relatively unchanged. When worked in the R-100 condition, however, explosive forming does not significantly alter the properties, while cold rolling has a decided detrimental effect on strength.

It should be pointed out that only a small amount of cold work (2.4%) in Condition T raised the yield strength by 10,000 psi. On a specific basis, a linear extrapolation to 10% strain would result in a 45,000 psi strength increase. Unfortunately, one of the problems is the instability strain limitation in the high-strength, transformed condition. Conceivably, then, substantial beneficial effects could be realized if the fabrication procedure does not involve large tensile strain components along with sizable compressive strains.

The influence of high energy rate forming in the A1750 condition on RH950 strength levels has led to some unusual results. For example, the yield strength after explosive TMP is 34% lower than that of the undeformed control material, and 30% lower than after conventional TMP by rolling to an equivalent strain. The decrease in ultimate strength is less severe (about 13% and 11%, respectively). Why the discrepancy is this great presents an interesting problem which has not yet been resolved. Presumably, the transformation characteristics are significantly altered at -100°F. Until such a time as the result is confirmed by additional experiments, the causes better understood, and modified heat treatment conditions determined and specified, one should temporarily avoid the application of this particular explosive TMP schedule. This investigator is confident, however, that an appropriate heat treatment can be found which will eliminate this strength discrepancy without the necessity of resolutionizing.

At this stage of the investigation, several tentative conclusions can be drawn. Firstly, 17-7PH stainless steel can be processed successfully by dynamic TMP, utilizing explosive forming in conjunction with the standard heat treatment schedules, without property degradation under the following

circumstances: when the initial state prior to working is Condition A or T, converted after forming to TH1050; Condition R-100 as the initial state, converted after forming to RH950. Secondly, explosive forming in Condition A and aging at 900°F (fractional Condition CH900) will not yield the expected properties achievable by an equivalent amount of reduction by cold rolling. Once this fact is known, it can be taken into consideration in designed for service, or alleviated by changing the heat treatment parameters. Thirdly, explosive forming in Condition A1750 and converting thereafter to RH950 according to normal procedures is to be discouraged until a modified heat treatment schedule is developed to restore properties to or above nominal levels. Lastly, although the explosive TMP of 17-7PH stainless steel does not seem to have led to any outstanding property improvements for the schedules investigated to date, neither does it introduce adverse effects which cannot be readily overcome.

The response of explosively formed and cold rolled Beta III titanium to aging at several temperatures is being studied also. Some of the more significant results are summarized in Table II.2.3. This table shows the percentage increases in hardness (DPH) due to aging for 4 and 8 hr. at 450, 700, and 900°F, and for 72 hr. at 450°F. The basis of comparison in (a) is the unstrained solution-treated control material, and in (b) the undeformed but similarly aged stock. There is a distinct hardening effect due to prior working with all aging times and temperatures examined. The smallest influence of TMP occurs at 900°F, which coincides with the precipitation of alpha phase. Moreover, the 900°F aged hardness after explosive forming is slightly lower than after an equivalent reduction by cold rolling. In both respects, the hardness data agree with previously reported tensile properties after an 8-hr 900°F age.

If, on the other hand, one considers the results for 450°F and 700°F, which are conducive to the precipitation of omega phase, then a TMP strengthening effect becomes evident. Whereas prior strain by cold rolling only marginally raised the strength level on aging at 700°F, explosive forming led to appreciable strength improvements. A similar but more pronounced effect occurred for a longer aging time at 450°F. It should be noted that the as-formed hardness was generally lower after explosive forming than after conventional working. This is not inconsistent with previous findings for BCC metals.

Consequently, the explosive TMP of Beta III titanium alloy seems to be encouraging. In addition, the above observations suggest that a two-step aging sequence could prove beneficial to overall properties.

Table II.2.3 Percentage Increase in Hardness (DPH) of Beta III Titanium Due to Aging After Forming to 10% Reduction in Thickness.

Forming History	4 Hr. 450°F	4 Hr. 700°F	4 Hr. 900°F	8 Hr. 450°F	8 Hr. 700°F	8 Hr. 900°F	72 Hr. 450°F
(a) Relative to the Undeformed, Solution-Treated State							
UD	18.3	51.8	52.1	21.6	59.0	60.3	23.5
CR	34.3	61.5	62.1	33.2	68.0	67.7	44.4
EF	33.6	75.2	58.2	33.6	78.4	64.9	56.7
(b) Relative to the Undeformed, Aged State							
CR	13.6	6.4	6.5	9.5	5.7	4.6	16.9
EF	12.9	15.4	4.0	9.8	12.2	2.9	26.9

3. Prediction and Control of Explosive Pressure History

Principal Investigators: M. A. Kaplan, G. A. Thurston

Graduate Students: V. D'Souza, G. Rowell

The explosive pressure-time history from the detonation of an axial charge in a thick walled hollow cylinder is being investigated by means of strain gages on the outside wall of the cylinder. It is possible to calculate the combination of peak pressure and duration from the strain gage readings on the outside of the cylinder wall.

Strain gages have a fast enough response time for this purpose, but some difficulties have been encountered with the circuitry, resulting in inconsistent readings. There is reason to believe that these difficulties have been overcome, and precise measurements will begin shortly.

Up to this time a stainless steel tube has been used to encase the charge. Future investigations will be directed toward replacing the stainless steel tube with a less expensive mild steel tube without decreasing the duration of the explosive pressure pulse below the critical value required for successful autofrettage.

The energy transfer from a centrally located charge through water to a circular blank is being investigated mathematically. A Kirkwood-Bethe strong shock analysis has been used to determine the energy transfer from the primary shock wave to the blank. For small stand-off distances, the curvature of the shock wave has been taken into account in the calculations. This part of the investigation has been completed and attention is now being focused on the reloading phenomenon following the primary shock wave.

At a small stand-off distance (L/D = 1/6) the gas bubble bursts over the blank. Analyses will be made to predict the resulting pressure on the blank and the duration of the energy transfer.

4. Explosive Welding

Principal Investigator: S. Carpenter

a. Diffusion and Defect Studies

Graduate Student: M. Nagarkar

Results of diffusion studies on both explosion welded and roll bonded copper-nickel couples have shown a definite enhancement of the diffusion in the explosion welded couples. To demonstrate that the enhancement is not a result of the wavy interface an explosion welded couple was fabricated using a symmetrical explosive loading arrangement. This gave an explosive weld with a straight interface. Diffusion studies on this couple also gave enhanced diffusion over that measured in the roll bonded couples. It is felt that the

enhanced diffusion is the result of a defect structure produced by the severe deformation and jetting along the weld interface. It is also felt that probably the most important feature of the defect structure is its thermal stability. At present work is underway to try and observe the defect structure by use of transmission electron microscopy. Thinning is very difficult because of the dual metal couple. To accomplish thinning an ion discharge system has been fabricated which essentially uses high energy ion bombardment to evaporate metal atoms off the surface.

Work is also continuing on studying the Fe-Ti system to see if formation of intermetallic phases is enhanced as the diffusion was in Cu-Ni welds. Samples have been welded and heat treated and data are now being taken using the electron microprobe.

b. <u>Welding Parameters and Thickness Limitations</u>

Graduate Student: R. Wittman

Previous investigations have indicated there is a unique collision angle for optimum weld strength of a particular metal-alloy combination. It is generally thought that the collision angle for optimum strength will remain constant as the flyer thickness is increased when using the parallel welding geometry and a constant explosive composition. If the collision angle remains constant for the parallel geometry and a particular explosive composition, then the flyer plate impact velocity will also be constant. But, if the flyer plate thickness is increased (i.e. increasing the plate mass), and the explosive conditions and stand-off are adjusted to maintain a constant impact velocity (collision angle), the kinetic energy of the flyer plate will have increased.

It has been observed that impact kinetic energy is dissipated in numerous ways during flyer plate-base plate impact. The most important mode of dissipation is deformation in the vicinity of the interface (i.e. the formation of a wavy interface). Deformation is accompanied by the generation of heat and a corresponding temperature rise, which can be extreme to the point of producing mechanical property degradation and lowered bond strength.

These observations would suggest that constancy of collision angle for increasing flyer plate thickness is not a proper model for uniform explosion weld strengths. The controlling factor determining impact angle would seem to be the impact kinetic energy. For constant thermal-mechanical results at the weld interface, the impact kinetic energy must remain constant. If this is true, the flyer plate impact velocity and collision angle must decrease as the thickness of the flyer plate is increased for a constant kinetic energy input corresponding to optimum weld quality.

Experiments have been completed for 6061-T6 aluminum welded to itself which are consistent with a constant kinetic energy model. In these experiments the explosive composition and welding geometry were maintained constant, while the explosive mass was varied for flyer plates ranging in thickness from 1/8 inch to 1 1/2 inches. The results show that for parent metal strength welds, the flyer plate impact kinetic energy had remained constant as the flyer plate thickness was increased. The impact velocity and collision angle have been observed by flash radiograph measurements to decrease with increasing flyer plate thickness.

It is certain there must exist a lower limit on impact velocity that will produce the necessary interface flow and resultant break-up of bond inhibiting contaminants. If the constant kinetic energy model is true, then there must be a limiting plate thickness which can be optimally welded. In the case of 6061-T6 aluminum, 1 1/2 inches thickness appears to be very near the limit that can be explosion welded to itself and result in parent metal weld strength.

5. Perforated Dies for Explosive Forming

Principal Investigator: A. A. Ezra

Postdoctoral Fellow: S. Kulkarni

Following the death of Professor H. S. Glick, this work has been taken over the Dr. A. A. Ezra, with the assistance of Dr. S. Kulkarni. The work has been re-directed toward the development of rational methods of analysis for thin walled dies for explosive forming.

Since explosive forming dies often fail due to sizing shots, a hemispherical die configuration is being analyzed for this loading condition. The differential equations of motion have been set up to include the resistance of the surrounding water. Experimental verification of some of the preliminary results will be carried out shortly.

6. Explosive Forming of Large Thick Walled Domes

Principal Investigator: R. J. Green

This work has been limited exclusively to theoretical investigations. A parallel experimental investigation has been funded separately from a different source as a spin-off contract.

This is another example of a direct coupling of science and technology. The theoretical work is being done under the auspices of this contract while the experimental work, which is directed toward a new technology for forming thick walled domes is being done for the U.S. Navy.

Using the sandwich approach where two domes are formed simultaneously it has been found that the explosive energy required may be estimated by the following formula

$$E = 27\,\sigma_o\,h_o\,w^2$$

where E = energy in the charge.

σ_o = yield stress of blank material

h_o = initial thickness of blank

w = depth of dome at center

The thickness distribution may be estimated from the following formula

$$h/h_o = 0.87\,(w/r\ )^2$$

where h = blank thickness

r = original radial distance from center of blank before deformation

7. Use of High Explosive Pressures for Increased Ductility

Principal Investigator: M. A. Kaplan

Work on this has been deferred until next year so that Professor Kaplan can complete his investigation on the prediction and control of pressure history for axial charges in thick walled tubes. These have been delayed due to experimental difficulties.

8. Analysis and Design of Facilities for Explosive Welding

Principal Investigator: A. A. Ezra

Graduate Student: A. Eriksen

A barrier to the technological exploitation of the research knowledge being generated is the necessity of using remote locations to shoot the large charges required for commercially useful applications of explosive welding.

A vacuum facility to reduce the noise level is being analyzed and designed. Comparative analyses have shown that a hemispherical shell is the most efficient structure. It has also been shown by analysis that a 22 ft. diameter hemispherical shell, one inch thick, can safely contain a 200 lb.

dynamite explosion, provided the air pressure in the shell is reduced to 1 psi before firing. Present thinking for the fabrication of such a container runs along the following lines. A truncated cone will first be fabricated and with the inside air at ambient pressure, a charge will be fired to expand it to the desired shape. For subsequent shots, the ambient pressure level will be reduced to 1 psi before firing.

Experimental investigation of a small scale model will be carried out shortly.

9. Explosive Fabrication of Steel Boiler Components

Principal Investigator: H. Otto

Graduate Student: James Boyter

Stock of 1/2-in. thick A-515 was explosively formed using two different procedures: (1) into flat bottom die and (2) simultaneous free forming of two blanks. In both cases the original blank diameter was 22 inches. Prior to forming, the blanks were photogridded so the circumferential and radial strains could be measured. Strains were measured and the effective strains along two diameters calculated using the Von Mises Henchy criteria. For comparison purposes, part of the stock was rolled in two directions to give a biaxial strain the same as that in specimens taken from the domes for Charpy and tensile testing. Specimens were taken orientated longitudinal and transverse to the original rolling direction in the plate stock.

Testing is currently underway, and the only series completed is Charpy impact tests taken from the flat bottom domes and compared with cold-rolled stock at the same strain (0.04). Charpy specimens of the as-received stock have been completed also. These results are presented in Figure II.9.1. As was expected, strain, regardless of mode, did increase the DBT of the steel. Although there is a lowering of the impact energy by straining the specimens at ambient conditions, elevated temperature tests were not conducted. Explosive forming had less of an effect on the DBT properties than cold rolling.

The increase in hardness at a comparable level of strain was about the same for both the cold-rolled and explosively formed stock (75 R_B as-received to about 85 R_B for the strained specimens).

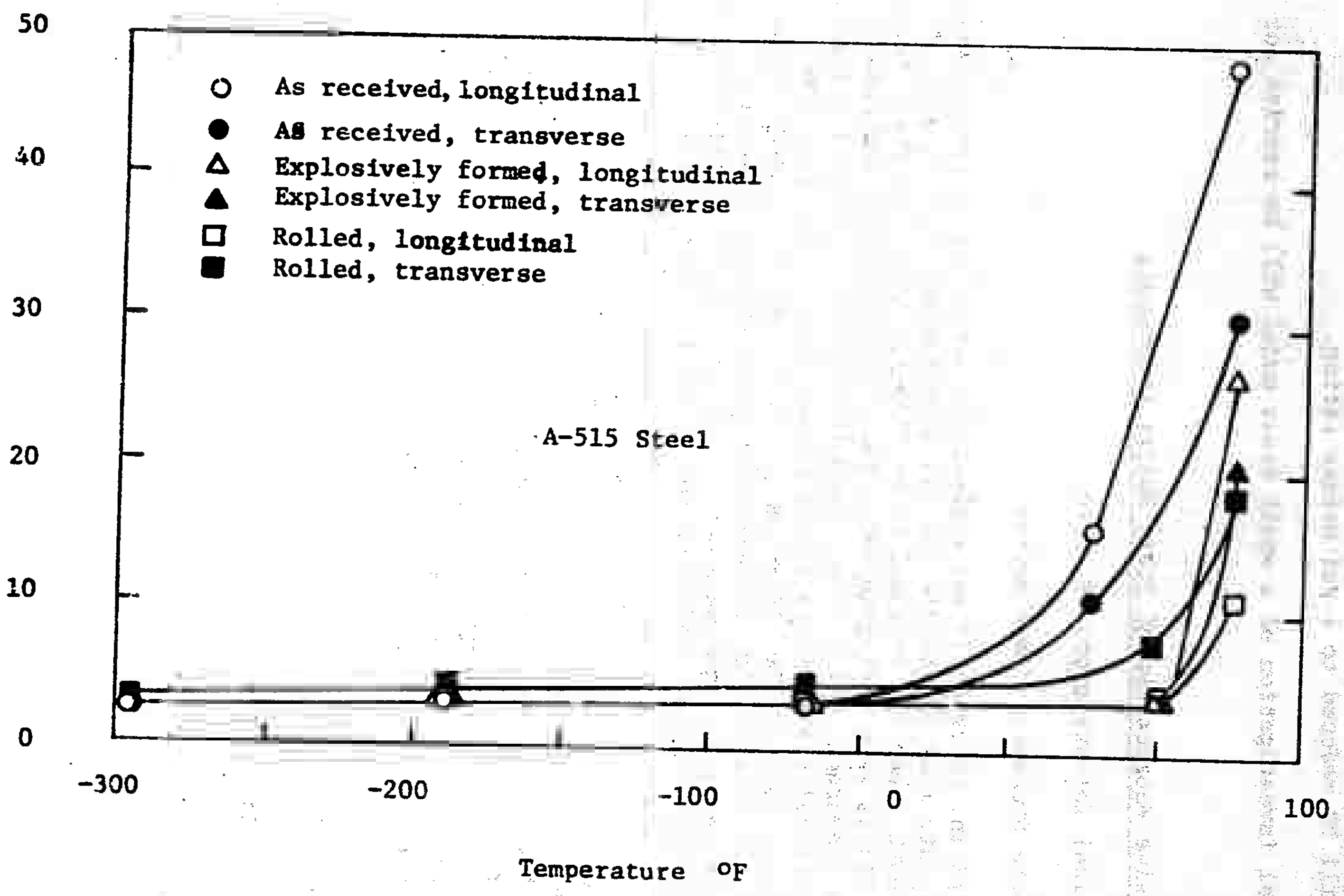

Figure II.9.1 Results of Charpy Impact Tests on A-515 Steel With an Effective Strain of 0.04 Introduced by Explosive Forming and by Cross Cold Rolling